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RESEARCH

Warmwater Stream Bank Protection and Fish Habitat: A Comparative Study

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ABSTRACT / Fishes and their habitats were sampled in Harland Creek, Mississippi, for 3 years to compare the relative value of three types of bank treatment in an incised, warmwater stream. Semiannual samples were collected from 10 reaches: 3 reaches protected by each of the three types of protection (longitudinal stone toe, stone spurs, and dormant willow posts) and an unprotected, slowly eroding bend. Protection of concave banks of bends had no measurable effect on the habitat quality of downstream riffles. Although bends and adjacent downstream riffles were faunistically similar at the species level, catostomids and centrarchids were more dominant in pools and smaller cyprinids more dominant in riffles. Reaches with willow posts were slightly deeper than the others, most likely because of geomorphic factors rather than bank treatment. Mean water surface widths in reaches stabilized with stone spurs were 40% to 90% greater than for other treatments, and current velocities were greatest in reaches with stone toe. Patterns of fish abundance and species diversity did not differ significantly among treatments. However, principal components analysis indicated that the fish species distribution associated with the untreated reference site was distinct. Reaches stabilized with stone spurs supported significantly higher densities of large fish and higher levels of fish biomass per unit channel length than reaches with other bank treatments, generally confirming previous research in the region. Initial costs for spurs were comparable to those for stone toe and about three times greater than for willow posts.

Stream reaches damaged by accelerated bank or bed erosion are often candidates for habitat restoration projects. Recently completed work indicates that stream habitats degraded by incision-related erosion may be rehabilitated using erosion control measures (Shields and others 1998a). Many techniques are available for streambank erosion control, and selection of the best technique for a given application should be based on the dominant erosion mechanism at the site in question, economic factors, and environmental considerations (Shields and Aziz 1992). Considerable evidence suggests intermittent structures like stone spur dikes are superior (in terms of effects on aquatic habitats) to continuous protection structures like revetment or stone toe (Shields and others 1995a). For example, Knight and Cooper (1991) reported a mean biomass catch per unit effort adjacent to stone spurs of 46 kg hour^{-1}, but only 8 kg hour^{-1} adjacent to stone toe protection. Restoration of woody vegetation on eroding banks is one of the most common approaches for stream ecosystem restoration, and initial costs of establishing woody vegetation may be less than the cost of placing structure (Coppin and Richards 1990). However, few studies have quantified the relative value of various bank treatments for restoring or enhancing the quality of warmwater stream habitat (e.g., Knight and Cooper 1991). Scientific information on low-gradient (or ''warmwater,'' sensu Winger 1981) stream restoration in general is also scarce relative to coldwater systems.

Pool habitats (relatively deep areas of low velocity) are typically in short supply in warmwater streams damaged by erosion or channelization relative to lightly disturbed streams (Shields and others 1994). Loss of pools is part of mutual adjustment of many variables within the fluvial system in response to disturbance related to channel widening, elevated sediment loads, and sometimes higher bed slope that results from channel straightening. Pools in streams disturbed by incision tend to be temporally unstable (Cooper and Knight 1987). Accordingly, one strategy for rehabilitating aquatic habitats along stream corridors damaged by incision is to use vegetation and structures to form and maintain stable pool habitats (Shields and others 1992), and this strategy has been at least partially effective when employed along channelized, incised streams elsewhere in this region (Shields and others 1998a).

KEY WORDS: Streambank erosion; Stream bank protection; Fish; Habitat; Stream restoration

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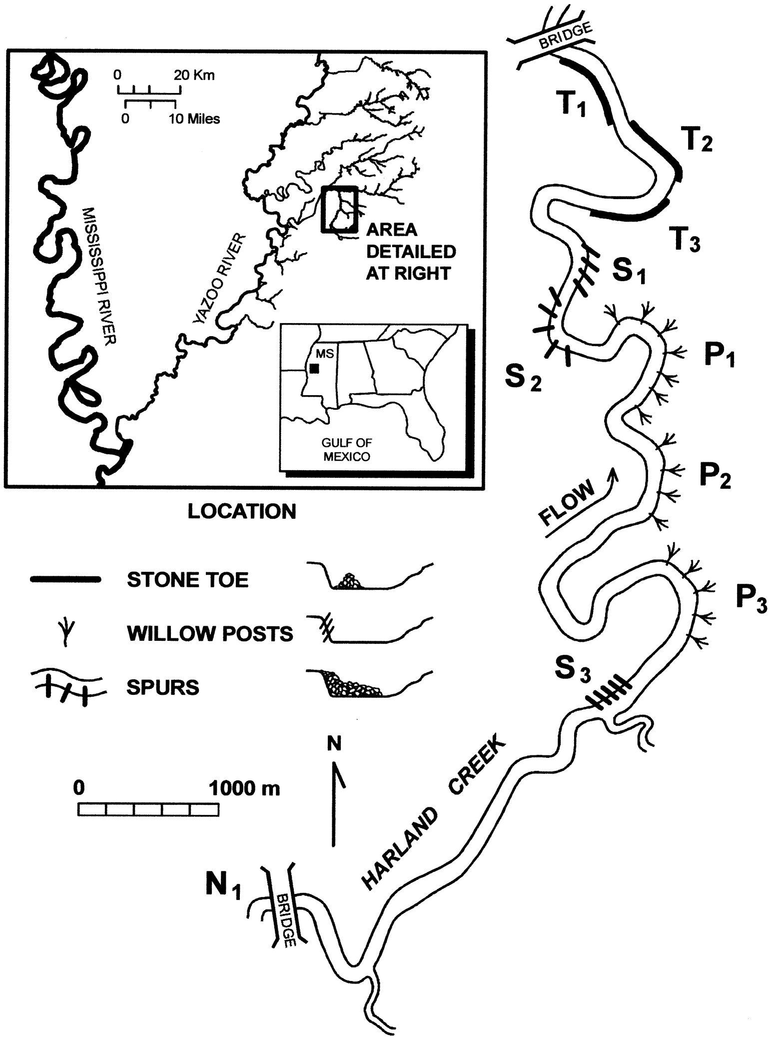

Figure 1. Location of study sites. Site designations indicate bank treatment (T = stone toe, S = spur dikes, P = willow posts, N = no bank treatment) and site number (subscript).

This paper presents results of a 3-year study of habitat and fish community response to three types of bank protection: stone toe, stone spur dikes, and dormant willow posts. A slowly eroding, unprotected bank was also sampled for comparison. Since stabilization of the concave banks of a meandering stream can have implications for adjacent riffles, we also sampled riffles downstream of the protected banks.

Study Site

Harland Creek is a fourth-order, meandering, sand and gravel-bed stream, draining about 80 km^2 of hilly, mostly forested lands in west-central Mississippi (Figure 1). Channel geometry and migration rates have been described by others (Neill and Johnson 1987, Watson and others 1997, unpublished data from C. Watson, 1997). These sources report bank heights varied from 1.6 to 12 m, channel widths averaged about 35 m, bed slope averaged about 0.001, and sinuosity was about 2 in our study reach. Comparison of air photos taken in 1955 and 1991 indicated extensive lateral migration and avulsion of meanders during that interval, with an average bank migration rate of 4.3 m year^{-1} (Watson and others 1997). Annual surveys in 1993 and 1994 indicated slight aggradation between survey dates in the study reach, averaging about 34 cm. Bed material was a mixture of sand and medium gravel with D_{50} between 0.30 and 13 mm and D_{84} between 0.89 and 25 mm (Doyle 1997). Well-defined pools occurred on the outside of bends adjacent to large sandy point bars, and there were one or more riffles between bends. Water quality was generally adequate to support aquatic life (Slack 1992), but elevated levels of suspended sediment (10^3 to 10^4 mg L^{-1}) occurred during high flows. Annual suspended sediment yield measured at a station about 6 km downstream averaged 1050 metric tons km^{-2} during water years 1987–1996.

a. Unprotected bank.

c. Willow posts.

b. Stone toe protection.

d. Stone spurs.

Figure 2. Typical views of Harland Creek study reaches with (a) unprotected banks, (b) stone toe, (b) dormant willow post plantings, (c) stone spurs.

Concave banks of bends in a 4-km reach of Harland Creek were stabilized in 1991–1994 using three techniques: stone spur dikes (also called bendway weirs), dormant willow post plantings, and longitudinal stone toe (Figure 2). Although some bends were stabilized using combinations of these methods, sampled bends were stabilized using only one of the three methods. Spur dikes were generally angled 10° to 30° upstream with sloping crests 0.6 m wide and were completed in September 1993. Dike lengths varied from about 6 to 12 m. Willow posts were dormant, living plant materials 8 to 30 cm in diameter by 3 m long and were planted 2.4 m deep using an hydraulic auger in February and March 1994. Longitudinal stone toe was a windrow of quarried limestone riprap with triangular cross section placed at the bank toe in 1991. Stone toe dimensions were controlled by the angle of repose and a fixed application rate of 3000–6000 kg m^{-1}. Construction costs for willow posts per unit length of bank protected were about one-third those for stone toe and about one-fourth that for stone spur dikes, but only about 41% of the willow posts survived longer than 15 months (Watson and others 1997). Additional description of the design, construction, and performance of the bank stabilization measures has been provided by Watson and others (1997) and Derrick (1997).

Methods

Protection schemes were placed on concave banks by the U.S. Army Corps of Engineers between 1991 and 1994 for erosion control. Design and construction proceeded independently from our study, and we had no control over the sequence or proximity of protection treatments to one another. We selected reaches to sample that contained only one type of treatment (some banks were protected with combined treatments) and that were reasonably free of influences not related to bank treatment.

Fish and their habitats were sampled semiannually in 10 reaches: 3 reaches protected by each of the three types of protection and an unprotected, slowly eroding bend (Figure 1). One of the reaches treated with willow posts was relocated from the bend just upstream from reach T3 (Figure 1) to P3 after the first year of study because the posts were replaced with stone toe protection. Sampling occurred at baseflow during June and October each year 1994 through 1996. Each sampled reach was composed of a 100-m-long bend segment with protection applied to the concave bank and a 20-m long segment located in the riffle immediately downstream from the protected bend. Bend segments were sampled to assess the local impact of the bank protection on habitats, while riffles were sampled to determine if bank protection and control of bank migration had indirect impacts on the quality of downstream riffles. Bend segment endpoints were fixed so that essentially the same area was sampled each time. The riffle segments were always located downstream of the associated bend segment, but were not tightly fixed in space because riffles tended to be dynamic features due to migration of bars. No riffle zone was found downstream of the unprotected bend, probably because of local channel modifications associated with a bridge crossing. At least one side of the stream in riffle segments was usually protected using the same form of protection applied to the associated bend segment.

Aquatic habitat conditions in bends were sampled by measuring depth and velocity using a wading rod and an electromagnetic current meter at five points along five transects running perpendicular to the channel at 20-m intervals. Along each transect the five sample points were located 0.75 m from each bank, and 25%, 50%, and 75% of the water surface width from the left water's edge. Surficial bed material was visually classified (e.g., sand, gravel, mud, debris, riprap, etc.) at each measurement point. Water width was measured at each transect, and notes were made regarding the number and size of woody debris formations, bank vegetation, and canopy. Riffle habitat conditions were sampled at 15 to 25 points along two transects running perpendicular to the channel 10 m apart. Depth, velocity, and bed type were recorded for each point as described above. Discharge was measured at least once each sampling day using a wading rod and current meter. Selected water quality variables (temperature, specific conductance, dissolved oxygen, and pH) were also measured in situ with a field instrument once each sampling day. Since maximum water depths in bends of meandering channels are proportional to the curvature of the bend, radii of curvature of bend segments were measured from contour maps shown on construction plans prepared by the U.S. Army Corps of Engineers (1993).

Fish were sampled using two backpack electroshockers simultaneously. After the lower end of each segment was blocked with seines, shocking crews proceeded from the upstream to the downstream end of the segment. Fish trapped in the seines were included in the sample. Fishes longer than about 15 cm were identified, measured for total length, and released. Smaller fish and fish that could not be identified in the field were preserved in 10% formalin solution and transported to the laboratory for identification and measurement. Comparison of electroshocking samples from similar streams with rotenone collections leads us to believe our approach captured about 10–20% of the resident fauna, not enough to influence results of semiannual sampling.

Analysis

Fall and spring habitat data were pooled and grouped by reach type (bend or riffle) and by bank treatment (none, stone toe, willow posts, spurs) for analysis, yielding sample sizes (N) for point data (depth and velocity) between 145 and 445, and between 6 and 18 for reach data (e.g., woody debris density, number of fish, number of fish species, etc.). Data were not normally distributed, so medians were compared using a one-way ANOVA on ranks (Jandel Corporation 1995). Variance of maximum depth (VMD) is a useful index of stream habitat quality (Jungwirth and others 1993, 1995). We computed a VMD for each reach and each sampling date using the maximum depth measured at each cross section. Resulting VMD values were then compared across bank treatments using ANOVA (Jandel Corporation 1995).

Electrofishing efficiency was apparently inversely proportional to water depth. Graphical and statistical analyses indicated that plots of biological variables against mean water depth for each bank treatment had homogeneous slopes. To test for differences in fish collections, analyses of covariance tests (PROC MIXED, SAS 6.12; SAS Institute 1989–1996) were used to compare fish density (numbers and biomass per 100 m of stream), large fish density (no. of fish with body length $\geq$ 7.5 cm per 100 m of stream), and species richness (number of species per 100 m of stream) using mean water depth as the covariate and sampling site and bank treatment as class variables (Steel and others 1997). This allowed us to compare the relative merits of the bank treatments without the confounding influence of different sampling efficiencies.

Numerical density of each fish species comprising at least 1% of the numerical catch from bend segments was examined by bank treatment. A nonparametric ANOVA (Kruksal-Wallis with Dunn's method for pairwise comparison) was employed for these tests (Jandel Corporation 1995). Means were not adjusted for depth effects on sampling efficiency.

Species composition and relative abundance were compared at the treatment and site levels by computing percent composition by numbers and by biomass for all species and for major faunal groups. Simple correlation coefficients were computed using the total collection list for each bank treatment. Morisita-Horn quantitative similarity indices (Magurran, 1988) were computed between the total collection from the unprotected site and each of the other sites. The Morisita-Horn index has been shown to be robust in the face of variations in sample size and diversity (Ross et al., 1985). The index ranges from zero (no similarity) to unity (identical collections). Values of the similarity index computed between total collections from each reach and the unprotected reach were compared by treatment using appropriate t-tests. Finally, faunal similarity among sites was explored using principal components analysis (Jandel Corporation, 1995) of the abundance of the 22 most common fish species. Sample units were plotted in multivariate space and physical attributes were correlated with leading principal components.

Results

Flows were between 0.11 and 0.30 m^3 sec^{-1} during field sampling (as measured at the downstream end of the study reach) except for one sampling day in spring 1995, when discharge reached 0.58 $m^3 sec^{-1}$. Water quality data indicated acceptable conditions for most native fauna; however, relatively high temperatures (24.2 to 30.8°C) were observed during summer baseflows. Continuous discharge and suspended sediment records compiled by the U.S. Geological Survey at a gaging station 6 km downstream indicated that conditions during the study were typical of those observed during the period of record (Table 1).

Physical habitat in the sampled reaches reflected morphologic factors as well as the impact of bank treatments. Bend segment radii of curvature ranged from 77 m to 142 m except for a reach with spurs which had a radius of 344 m. Radii means and ranges for all treatments except spurs were similar; average bend radius for spurs was elevated by the single long-radius bend (Table 2). Water depth in bends is inversely related to the bend radius when the bend radius is greater than about two channel widths (Thorne 1992). Accordingly, water depths in the long-radius spur reach were lower than for the other reaches with spurs.

Table 1. Discharge and suspended sediment means and maxima for Harland Creek near Howard, Mississippi

Time period	Mean (max) daily discharge, m^3 sec^{-1}	Mean (max) sediment load, metric tons day^{-1}
Years encompassing this study (1994–1996)	2.71 (117)	373 (32,020)
Period of record (water years 1987–1996)	2.65 (123)	462 (49,640)

Table 2. Radii of curvature for bends containing study reaches

Type of bank protection	Radii of curvature, m
No structure	108
Stone toe	90, 103, 135
Willow posts	94,[a] 100, 142
Spurs	77, 98, 344

[a] During the first year of the study, another post site was used that had a radius of 54 m. This site was replaced for the final 2 years of the study because the posts were replaced with stone protection.

Physical data revealed subtle differences in habitat quality among bank treatments (Tables 3 and 4). Statistical results shown in Table 3 were unchanged when data collected during the single higher flow (spring 1995) were excluded from the analysis. Differences in water depth were greater when the upper ends of the distributions were considered. The 75th percentile for water depth for no structure, toe, posts, and spurs were 42, 43, 62, and 54 cm, respectively. Additional observations include:

- The reach with no structure was relatively slowly flowing and shallow, and had heavily vegetated banks and abundant woody debris and organic substrate. The average variance of maximum depth (VMD) was more than twice as great as for other reaches, indicating more overall physical habitat diversity. However, VMD differences were not statistically significant.
- Reaches with stone toe were shallow and swift, with relatively abundant stone riprap substrate. Although they had well-vegetated banks and relatively good canopy, they retained little woody debris (Table 4).
- Reaches with willow posts were wide and had greatest depth, with low current velocities. Although all

Table 3. Baseflow physical habitat conditions in bend reaches, Harland Creek, 1994–1996. The *N* values are number of depth and velocity measurements. Different subscripts indicate distributions are significantly different ($P < 0.05$, Kruskal-Wallis ANOVA on ranks and Dunn's method for pairwise multiple comparisons)

Type of bank protection	Mean (median) water depth, cm	Mean (median) variance of maximum water depth, cm	Mean (median) water width, m	Mean (median) current velocity, cm sec^{-1}
No structure $N = 145$	32 (24)$_a$	1602 (1304)$_a$	7.1 (6.6)$_a$	7 (3)$_a$
Stone toe $N = 447$	31 (25)$_a$	682 (580)$_a$	7.8 (7.5)$_a$	10 (6)$_b$
Willow posts $N = 445$	44 (40)$_b$	796 (578)$_a$	9.4 (9.0)$_b$	5 (3)$_a$
Spurs $N = 422$	37 (29)$_a$	785 (492)$_a$	13.5 (13.9)$_c$	7 (3)$_a$

Table 4. Selected physical variables for aquatic habitat in bend reaches, Harland Creek, 1994–1996. The *N* values indicate the number of times reaches with the given treatment were sampled. Different subscripts indicate distributions are significantly different ($P < 0.05$, Kruskal-Wallis ANOVA on ranks and Dunn's method for pairwise multiple comparisons)

	Mean (median)			Percent bed covered by		
Type of bank protection	Debris density, % of water surface	Woody vegetation cover on banks, %	Canopy over baseflow channel, %	Most common bed type	Second most common bed type	Third most common bed type
No structure $N = 6$	14 (15)$_a$	55 (50)$_{a,b}$	47 (42)$_a$	51 (gravel)	25 (sand)	8 (clay)
Stone toe $N = 18$	2 (2)$_b$	68 (70)$_a$	47 (48)$_{a,c}$	43 (gravel)	26 (sand)	14 (riprap)
Willow posts $N = 18$	16 (16)$_a$	51 (50)$_b$	36 (37)$_{a,c}$	42 (gravel)	33 (clay)	19 (sand)
Spurs $N = 18$	1 (1)$_b$	56 (55)$_{a,b}$	22 (15)$_b$	41 (gravel)	28 (sand)	15 (clay)

reaches had beds dominated by sand and gravel substrates, clay (including both recent deposition (mud) and consolidated strata exposed by erosion) was most common in post reaches, comprising more than 30% of the bed type classifications there (Figure 3 and Table 4). Because of the posts (considered woody debris in this evaluation) and the debris trapped by posts, reaches with willow posts exhibited levels of woody debris density roughly equivalent to the untreated reach and an order of magnitude higher than reaches with stone toe or spurs.

- Reaches stabilized with stone spurs were widest. Clay and riprap comprised about 15% and 5%, respectively, of the bed type classifications. Canopy and debris density were lowest for reaches with spurs (Table 4).

Riffle zones were usually gravel-bedded with depths <20 cm and current velocities between 0.05 and 0.4 m sec^{-1}. Conditions for the stone toe riffle zone at the extreme downstream (northern) end of our study area were strongly influenced by a bridge crossing immediately downstream (Figure 1). This riffle zone was sandy, considerably deeper (mean depth = 28 cm), and had much slower current (mean velocity = 6 cm sec^{-1}) than other riffle areas. However, when data from this zone were excluded from the analysis, there were no signifi-

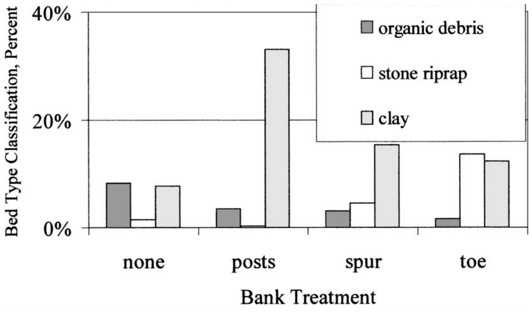

Figure 3. Distribution of bed types other than sand and gravel. Beds in all reaches were 20% to 30% sand and 40% to 50% gravel.

Table 5. Physical habitat conditions in riffle reaches, Harland Creek, 1994–1996. The *N* values are number of depth and velocity measurements. Data from one stone toe riffle zone are omitted because it was affected by a bridge crossing. Different subscripts indicate distributions are significantly different ($P < 0.05$, Kruskal-Wallis ANOVA on ranks and Dunn's method for pairwise multiple comparisons)

Type of bank protection	Mean (median) water depth, cm	Mean (median) current velocity, cm sec^{-1}	Mean (median) debris density, m^2 km^{-2}
Stone toe $N = 221$	16 (13)$_{a}$	25 (21)$_{a}$	2 (0)$_{a}$
Willow posts $N = 318$	13 (10)$_{b}$	27 (25)$_{a}$	2 (1)$_{a}$
Spurs $N = 336$	13 (10)$_{b}$	23 (19)$_{a}$	3 (0)$_{a}$

cant differences in riffle current velocities among bank treatments, and differences in depth were small (Table 5). Woody debris densities for riffles were similar for all treatments.

Fish collections from bend segments were highly variable in time and space and yielded from two to 958 individuals representing one to 21 species. Riffle collections ranged from 5 to 3053 individuals and 3 to 20 species. In all, 46 species of fish were collected during the course of the study. Forty-three of these species were taken from the 10 100-m reaches in bends, and 38 were obtained from the 9 shorter (20-m) reaches located in riffles. Over the course of the entire study, each riffle yielded 16 to 28 species (mean = 22) except for the aforementioned riffle impacted by bridge crossing modifications. This site yielded only 12 species. Riffles and bends supported similar assemblages—35 species were found in both types of reaches. Just eight species were found exclusively in bends, whereas three were found only in riffles, and none of these were abundant. The simple correlation coefficient between bend and riffle total collections (27 most abundant species) was 0.994. The lists of the four most common species for bends and for riffles were identical.

Minnows (family Cyprinidae) dominated all collections, comprising 82% of the catch from bends and 90% of the catch from riffles. The order of dominance for the four most common cyprinids, *Pimephalus notatus, Cyprinella camura, Campostoma anomalum,* and *Luxilus chrysocephalus*, was the same for bends and riffles. In both habitat types, about 2% and 1% of the fish were darters (family Percidae) and catfishes (Ictaluridae), respectively. Suckers (Catostomidae) and sunfish (Centrarchidae) comprised 11% of the catch by numbers from bends, but only 4% of the catch from riffles.

As noted in the Methods section, fish density and species richness were inversely related to mean water depth for all bend segments, with correlation coefficients, r = −0.56, −0.49, and −0.68, for numerical density, biomass density and species richness, respectively ($P < 0.0001$ for all). Least-squares means, adjusted for differences in water depth, were computed for each bank treatment via ANCOVA. There were no statistically significant differences in numerical fish density or species richness, but adjusted mean biomass (g of fish per 100 m of stream) was significantly greater for spurs than for posts or toe (Table 6). Reaches stabilized with spurs supported 2.1 and 1.6 times as much biomass as reaches with posts and toe, respectively.

Riffles were sampled more efficiently than bends due to their relatively shallow depths and narrow widths and were evidently heavily used by small fishes. Riffles yielded an average of 5 times as many fish and 2.5 times as much fish biomass per unit of sampling effort (unadjusted for effects of depth on sampling efficiency) than did bends (compare Tables 6 and 7). Fish taken from riffles tended to be smaller (mean length = 5.2 cm) than those from bends (mean length = 6.1 cm). Even though riffle zones were only one-fifth as long as bend sampling zones, riffles yielded comparable numbers of species per collection (means for bends and riffles were 10.4 and 11.4, respectively). ANOVA results indicated no significant differences in fish density or species richness among riffles based on bank treatment (Table 7). Data from the riffle impacted by the bridge crossing (T1, Figure 1) were excluded from ANOVA, as these data depressed values for stone toe.

Numerical densities of each the 16 most abundant fish species and of large fish (length $\geq$ 7.5 cm) in bend segments were similar for the three types of bank protection. Numerical densities of individual species were not correlated with water depth, so distributions were compared using a nonparametric test. Three species were more common along the unprotected natural bank than for the banks protected by willow posts (Table 8). Mean density of large fish was greatest in reaches protected with spurs, followed by stone toe, no protection, and willow posts. However, statistically significant differences in median densities of large fish were limited to the difference between spurs and willow post reaches (Table 9).

Relative abundance and species composition varied little among bank treatments. However, the cyprinids *C. camura* and *P. notatus* comprised 60% of the catch from protected reaches in bends, but only 31% of numbers taken from the unprotected reach. Simple correlation coefficients between total collections from each bank

Table 6. Summary of fish collections from bends, Harland Creek, 1994–1996. The N values indicate the number of times reaches with the given treatment were sampled. Means are least-squares means adjusted for differences in mean water depth due to effect of water depth on electrofishing efficiency. Different subscripts indicate that means are significantly different ($P < 0.05$)

Type of bank protection	Mean (SE) number of fish per 100 m	Mean (SE) biomass of fish per 100 m, g	Mean (SE) number of species per 100 m	Total number of species captured in entire study
No structure $N = 6$	392 (118)$_a$	638 (217)$_{a,b}$	13.6 (1.5)$_a$	30
Stone toe $N = 18$	120 (63)$_a$	654 (118)$_a$	10.8 (0.8)$_a$	31
Willow posts $N = 18$	181 (57)$_a$	482 (117)$_a$	10.7 (0.8)$_a$	35
Spurs $N = 18$	304 (61)$_a$	1034 (113)$_b$	12.4 (0.8)$_a$	35

Table 7. Summary of fish collections from riffles, Harland Creek, 1994–1996. The N values indicate the number of times reaches with the given treatment were sampled. Data from one stone toe riffle zone are omitted because it was affected by a bridge crossing. Different subscripts indicate distributions are significantly different ($P < 0.05$, Kruskal-Wallis ANOVA on ranks and Dunn's method for pairwise multiple comparisons for numbers, ANOVA on values for no. of species/100 m)

Type of bank protection	Mean (median) number of fish per 100 m	Mean (median) biomass of fish per 100 m, g	Mean (SD) number of species per 20 m	Total number of species captured in entire study
Stone toe $N = 12$	780 (615)$_a$	1605 (1,741)$_a$	10.9 (2.6)$_a$	34
Willow posts $N = 18$	880 (640)$_a$	1554 (1,493)$_a$	13.0 (1.8)$_a$	33
Spurs $N = 18$	1680 (635)$_a$	2560 (1978)$_a$	11.8 (3.8)$_a$	34

treatment (using only the 27 most abundant species) ranged from 0.94 to 0.99. The average values of Morisita-Horn quantitative similarity indices between the total collections from the unprotected bend segment and the segments protected with toe, posts, and spurs were 0.57, 0.51, and 0.66, respectively. Principal component analysis revealed patterns in species distributions among sites corresponding to physical gradients. Three components, PRIN1, PRIN2, and PRIN3, together accounted for 79% of data set variance, but no species was highly correlated with any of the three (loadings < 0.43). PRIN1 was weakly associated with the abundance of *Campostoma anomalum* and *Lepomis megalotis*, two species positively intercorrelated in abundance ($r > 0.87$, $P < 0.0005$). PRIN1 was also positively associated with mean velocity and negatively associated with mean depth and the presence of clay substrate. PRIN2 was positively associated with the abundance of *Lythrurus umbratilis* and *Gambusia affinis*, which were intercorrelated in abundance ($r = 0.98$, $P < 0.0001$). PRIN2 was positively associated, albeit weakly, with the presence of debris. PRIN3 was positively associated with abundance of *Etheostoma whipplei* and mean water width. Eleven sites, consisting of one site without bank protection, three sites with stone toe, four with willow posts (one site was replaced after the first year of the study), and three with spurs plotted in three-dimensional space revealed a cluster of nine sites with two outliers (Figure 4). Outlying points represent the site without bank protection and the widest, deepest spur dike site. Regions corresponding to bank treatment type overlap one another.

Distribution of fish biomass among gross faunal groups for total collections display interesting variation among the treatments. For example, the clupeid *Dorosoma cepedianum* comprised 11% of biomass from willow post and spur collections, but only 3% and 6% of the collections from the shallower and swifter unprotected and stone toe reaches, respectively. Ictalurids and catostomids (catfishes and suckers) comprised 17% of the

Table 8. Mean (median) numbers per 100 m of stream for selected fish species, Harland Creek, 1994–1996. The N values indicate the number of times reaches with the given treatment were sampled. Different subscripts indicate distributions are significantly different ($P < 0.05$, Kruskal-Wallis ANOVA on ranks and Dunn's method for pairwise multiple comparisons)

Type of bank protection	*Lepomis machrochirus*	*Campostoma anomalum*	*Pimephalus notatus*
No structure $N = 18$	11 (6)$_a$	68 (24)$_a$	83 (44)$_a$
Stone toe $N = 18$	4 (3)$_{a,b}$	9 (1)$_{a,b}$	39 (24)$_{a,b}$
Willow posts $N = 18$	2 (1)$_b$	3 (0)$_b$	34 (0)$_b$
Spurs $N = 18$	6 (4)$_{a,b}$	28 (9)$_{a,b}$	120 (37)$_{a,b}$

Table 9. Density of large fish, Harland Creek, 1994–1996. The N values indicate the number of times reaches with the given treatment were sampled. Means are least-squares means adjusted for differences in mean water depth due to effect of water depth on electrofishing efficiency. Different subscripts indicate that means are significantly different ($P < 0.05$)

Type of bank protection	Mean (SE) number of fish longer than 7.5 cm per 100 m
No structure $N = 6$	19 (8)$_{a,b}$
Stone toe $N = 18$	27 (5)$_{a,b}$
Willow posts $N = 18$	19 (5)$_a$
Spurs $N = 18$	37 (5)$_b$

biomass from post reaches and 19% of biomass from spur reaches, but only 8% and 11% of collections from unprotected and stone toe reaches, respectively.

Discussion

Key differences among bank treatments are shown schematically in Figure 5. Physical habitat quality differed only slightly among reaches of Harland Creek with different bank treatments. Differences likely reflected morphologic factors as well as bank treatments. Although greatest water depths occurred in reaches with willow posts, this was probably because of the cohesion of bank soils and bend geometry rather than the presence of the posts. In contrast to posts, the greater widths in reaches with stone spurs were likely related to spur placement (Shields and others 1998a). Mean water depth for spurs was depressed by conditions in the low-radius bend. Spur reaches provided water widths 30% to 50% greater than other reaches, consistent with findings by Shields and others (1998a), who found addition of stone spurs produced a 14% increase in baseflow water width in a smaller Mississippi stream.

We hypothesize that bank treatments were associated with relatively small gradients in physical habitat characteristics because overall habitat quality in Harland Creek was not severely impaired. Aquatic habitat quality in all reaches was superior in many respects to habitat quality in incised streams in nearby watersheds. Another study reported mean woody debris densities, woody vegetation cover on banks, and canopy over the baseflow channel in 24 incised channels in north-central Mississippi were lower than for the Harland Creek study sites (Shields and others 1995b). In addition, on average, more than half of the stream bed areas were covered by shifting sand, and mean water depth was only 20 cm. In contrast, Harland reaches were less than one-third sand-bedded and had mean water depths ranging from 31 to 44 cm. Harland Creek may have been superior to these sites because they had been straightened, and it remained sinuous.

We expected to observe fewer, but larger fishes and more species of fishes in reaches of Harland Creek with deep, stable pools than in shallow, less stable reaches. These expectations were in accord with the framework of warmwater stream fish communities proposed by Schlosser (1987) and used to partially explain response of fish communities to restoration (Shields and others 1998a). Even gradients in width, depth, and velocity as slight as those documented in Table 3 have resulted in significant shifts in degraded warmwater fish communities toward patterns found in lightly degraded reference streams (Shields and others 1998a). Generally, addition of pool habitat has elevated fish biomass. In this study, however, fish collections from the deeper post reaches yielded significantly less biomass than spur reaches. Perhaps this was because the cover provided by posts was decidedly inferior to that produced by stone spurs. The posts were rather uniformly arranged arrays of vertical cylinders (Figure 2c) lacking the wide gradation of three-dimensional spatial niches found in stone spurs or natural debris jams. The higher levels of fish biomass found in the spur reaches appear consistent with reports by Knight and Cooper (1991) and Shields and others (1998a, 1998b) based on studies of similar

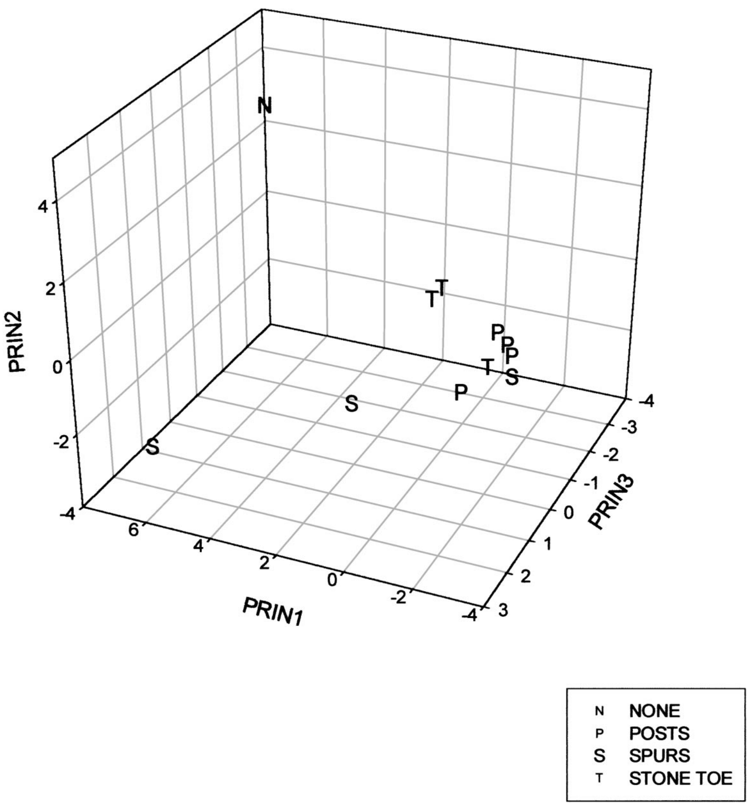

Figure 4. Principal components analysis of fish collections from Harland Creek: position of sampling units (sites) in multivariate (fish species) space.

streams in the region. Shields and others (1998a) found levels of fish biomass elevated by a factor of 15 following addition of extensions to stone spurs to promote scour hole maintenance, while Shields and others (1998b) reported 20% higher fish biomass in a reach with stone spurs added to toe protection than in an adjacent reach with only stone toe. Larger fish (>7.5 cm long) were also less common in post reaches than spur reaches and have been associated with spurs in other studies (Knight and Cooper 1991, Shields and others 1998a, 1998b).

Principal components analysis revealed patterns of fish species abundance were sensitive to physical gradients. The untreated site, though shallow, had relatively high levels of physical diversity, riparian canopy, and woody debris density, perhaps contributing to highest levels of fish numbers and species richness (Table 6) and a distinctive fish species distribution (Figure 4). Accordingly, in lightly degraded incised streams, refraining from controlling bank erosion and allowing natural channel evolution to restore habitat values may be the best approach. However, social, economic and political factors must be considered (Shields and others 1999).

Bend segments and adjacent downstream riffles were faunistically similar at the species level, yielding roughly the same numbers of species. Species composition

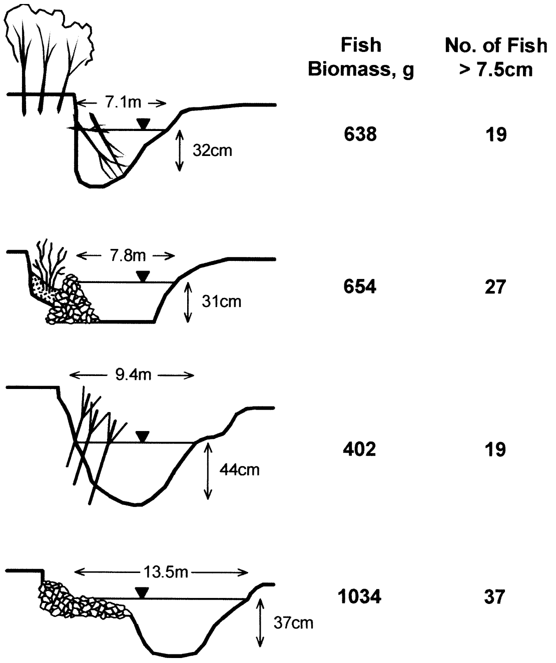

Figure 5. Schematic of bank treatments with means for selected physical and biological variables.

produced high values of similarity indices between bends and riffles despite their obvious physical differences. Similar observations were reported for a third-order stream in northeastern Oklahoma (Bart 1989). However, when fish collections from bends and riffles were sorted among broad faunal groupings, slight differences emerged, with catostomids and centrarchids more dominant in pools and smaller cyprinids more dominant in riffles. On average, fish from riffles tended to be smaller than those from pools.

Riffles located at bend inflection points (thalweg crossings) in meandering streams are are normally shallower and wider (Hey and Thorne 1986) and perhaps more stable than bend apices. Accordingly, bridge crossings over small streams are often located over riffles. Since embankments for bridge approaches constrict flood flows, the hydraulic patterns responsible for riffle maintenance at high flows are modified, and riffle habitat may be degraded. Such was the case in this study for the riffle at the extreme downstream end of the study area (Figure 1). Furthermore, there was no riffle downstream of our unprotected reach, and presumably it was totally eliminated by a bridge crossing.

Willow post planting cost only about one-third as much as stone toe construction (Watson and others 1997). Based on information provided by Derrick (1997), treatment with spurs cost \$98 to \$131 m^{-1}, which was roughly the same as for stone toe. In the Harland Creek setting, therefore, spurs evidently offer a superior ecological outcome for about the same cost as stone toe. Willow posts, though much less costly, were less reliable and less desirable from a fish habitat standpoint.

Field studies offer less ideal conditions than laboratory experiments, and many variables cannot be controlled. Typically, stream studies compare adjacent reaches on the same stream, ignoring the effects the reaches may have on one another, or similar reaches of adjacent streams, ignoring differences between streams. This study is an example of the former approach. This approach is warranted, however, because laboratory stream ecosystems may not be sufficiently realistic. Physical habitat–related gradients in fish communities across adjacent reaches with different bank treatments have been measured in other streams in this region (e.g., Shields and others 1998b). Our comparison of stone toe constructed in 1991 with spur and post treatments placed in 1993–1994 may bias slightly against the stone toe, since previous work suggests that fish numbers and biomass gradually decline following placement of stone toe (Knight and Cooper 1991). Other studies indicate that stone spurs retain or increase their habitat values during the first few years after construction. Observation of willow posts along Harland Creek indicates that their influence on habitat will diminish with time as many of them die and disappear (Watson and others 1997, Shields and others, 1998c).

Conclusion

Stone spurs (also known as bendway weirs) were slightly superior to longitudinal stone toe and willow posts for fish habitat rehabilitation in Harland Creek, a warmwater stream damaged by channel incision. Spurs produced a greater volume of pool habitat per unit channel length because of their effects on water width. Reaches stabilized with spurs supported 1.6 to 2.1 times as much biomass per unit channel length than did reaches with other bank treatments. Densities of large fish were also greater adjacent to stone spurs than willow posts. However, species diversity and fish abundance did not differ among treatments. Reaches with structural bank protection had woody debris densities about an order of magnitude lower than an unprotected reach or reaches stabilized with willow posts. Principal components analysis suggested that none of the bank treatments resulted in fish species distribution typical of the untreated reach. Protection of concave banks of bends had no measurable effect on the habitat quality of downstream riffles; however, riffle habitats were apparently adversely impacted by bridge crossings.

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